Comment on: "A test of the englacial thrusting hypothesis of 'hummocky' moraine formation"

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Areas of apparently chaotically organised moraine mounds and ridges are commonly associated with British Younger Dryas glaciers, and are also found at many contemporary glacier margins (Boulton & Eyles 1979; Benn 1992; Bennett & Boulton 1993b; Hambrey *et al.* 1997). Particularly in the British context, such landforms have commonly been referred to as 'hummocky' moraine. Whilst this term is undoubtedly an apt description of their morphology, genetic connotations have become attached to it, with some authors using it exclusively to refer to sediment-landform associations associated with wasting ice (e.g. Benn & Evans 1998: p. 483). Work undertaken over the last two decades has demonstrated that British Younger Dryas 'hummocky' moraine only rarely formed in association with stagnant ice, and it is now clear that they are polygenetic in origin (e.g. Benn 1992; Bennett & Boulton 1993b). For this reason the non-genetic, and similarly descriptive, 'moraine-mound complex' has been proposed for features of undetermined origin (Bennett *et al.* 1996b), and this term is adopted here.

Current ideas on the origin of British Younger Dryas moraine-mound complexes

Working in the early 1990s, Benn (1990; 1992) and Bennett (1991; Bennett & Boulton 1993b) independently demonstrated that many Scottish Younger Dryas moraine-mound complexes are composed of: (i) chains of mounds and ridges oriented across valley, interpreted as ice-marginal moraines; (ii) linear downvalley-oriented elements, interpreted as flutes and small drumlins; and (iii) areas of mounds in which no morphological organisation is discernible, interpreted as local stagnation deposits. The cross-valley moraines are the dominant component, and several models have been developed to explain their origin. These models variously interpret the landforms as ablation moraine, push moraine, and ice-contact fans (Eyles 1983; Benn 1990; 1992). The fact that none of the models are appropriate for all of the landforms reflects the importance of a variety of controlling factors including local basin form, as well as climatic and associated glacier activity gradients, and means that no single set of palaeoclimatic conditions can be inferred from the presence of a moraine-mound complex. Since the late 1990s, it has been argued that some moraine-mound complexes, both in Scotland and other upland regions of Britain, may have resulted from englacial thrusting, producing ridges predominantly oriented perpendicular to ice flow but which do not represent ice-marginal positions (Hambrey *et al.* 1997; Bennett *et al.* 1998; Graham & Midgley 2000; Midgley 2001; Graham 2002). This work has added to the range of process-based models available to explain the origin of moraine-mound complexes, and does not supersede any of the others.

The work of Lukas (2005)

Lukas (2005) presented detailed evidence on the formation of moraine-mound complexes in the northwest Highlands of Scotland. This is a valuable contribution because it adds to the available evidence on the internal structure, morphology and origin of such features. Following detailed sedimentological and limited morphological investigations, Lukas (2005) argued that the landforms he examined are principally composed of nested suites of terrestrial ice-contact fans that have experienced varying degrees of modification by overriding and ice-marginal pushing. On the basis of the evidence presented, we are confident that Lukas (2005) is correct in his assertion that the moraines described represent a primarily ice-marginal sediment-landform association. We also agree with the assertion that in the northwest Highlands, "readvances were the norm during the incremental, oscillatory glacier retreat in the Younger Dryas" (p. 303). Indeed, this is entirely consistent with evidence presented by others and ourselves from Scotland, both within (Bennett & Boulton 1993a; 1993b) and outside (Bennett & Glasser 1991; Benn 1992; Graham 2002) the limits of the Highland Icefield, and from the English Lake District (McDougall 2001; Graham 2002). Such punctuated recession is characteristic of glaciers with a wet-based thermal regime (e.g. Evans & Twigg 2002). Furthermore, numerous examples of small-scale erosional features (particularly striations) provide unambiguous evidence of wet-based conditions during the Younger Dryas (Gray & Lowe 1982; Glasser & Bennett 2004).

Given the well-established polygenetic nature of British Younger Dryas moraine-mound complexes, the way Lukas (2005) chose to frame his research question is surprising and misleading. The title set up the paper as "a test of the englacial thrusting hypothesis" (Lukas 2005: p. 287). It aimed to establish "…which of the two models [englacial thrusting/ice-marginal deposition] applies to the Scottish palaeo-context" (p. 289), the implication being that only one model is valid. The brief review above indicates that there are several, non-mutually exclusive, models; indeed it is well established that moraines with a variety of origins commonly occur in close association with one another within individual moraine-mound complexes (Benn 1990; Bennett 1991; Benn *et al.* 1992; Bennett & Boulton 1993b).

Evaluation of the Lukas (2005) approach

In attempting to 'test' the englacial thrusting hypothesis, we believe that Lukas (2005) made his case using two flawed arguments. The first flaw relates to the way he chose to test the hypothesis; the second to the conclusions he drew as a result of this test.

It is easy to 'accept' or 'reject' any scientific hypothesis if the test applied is based on inappropriate questions, or the questions are asked at inappropriate places. A fair test of the englacial thrusting hypothesis requires that we visit sites where thrusting has been proposed; or at least apply some objective criteria to identify similar sites. The first flaw in Lukas' argument was to test the validity of the thrusting hypothesis in an area where it has never been proposed as a mechanism for moraine genesis. Indeed, whilst Lukas (rightly) emphasised the value of sedimentary evidence in determining moraine genesis, at these sites it is not necessary because the morphology described is markedly different from that described for englacial thrust moraines (both in Svalbard and the UK). It is therefore not surprising that Lukas (2005) found no evidence of thrusting at his field sites.

The second flaw in Lukas' argument followed directly from the first and relates to the nature of scientific 'proof'. Lukas (2005) erred by taking the absence of evidence for thrusting at the sites he examined to be evidence that englacial thrust moraines do not exist anywhere, arguing that "the most important implication of this work is that englacial thrusting is not a mechanism that can explain the formation of Scottish ice-marginal 'hummocky' moraines…" (p. 305). In fact, our own position is not too far from that of Lukas. We agree that englacial thrusting cannot explain the formation of *most* moraine-mound complexes, and have never argued that it can. Indeed, we have explicitly stated that: "It is not proposed that englacial thrusting explains all 'hummocky moraine' or that it is particularly widespread within British Younger Dryas glaciers"

(Bennett *et al.* 1998: p. 31). It is quite possible (indeed probable) that both ice-marginal and englacial thrusting models are applicable in particular circumstances.

Whilst Lukas (2005) framed his research question as a test of competing hypotheses, he showed a determination to discredit the englacial thrusting hypothesis from the start. In his review of models of moraine formation, Lukas cited Woodward *et al.* (2002; 2003) who questioned the significance of thrusting in debris elevation in Svalbard glaciers based on observations at Kongsvegen, Svalbard. However, he failed to acknowledge that this work has been severely criticised by Glasser *et al.* (2003) for misrepresenting earlier structural-glaciological work, for over-interpreting the nature of changing flow dynamics from aerial photographs, and for presenting no new data to support their alternative hypothesis (injection of saturated sediment into basal crevasses). Lukas (2005) also failed to acknowledge subsequent sedimentological and isotopic work undertaken at Kongsvegen that supports the thrusting hypothesis (Hubbard *et al.* 2004). There is now a considerable body of evidence that thrusting may elevate subglacial sediment in certain circumstances. This evidence is reviewed by Graham *et al.* (in prep.) and summarised in Table 1.

Similarly, in the Scottish context, Lukas (2005) cited Wilson & Evans (2000) and stated that the moraines interpreted as englacial thrust moraines by Bennett *et al.* (1998) in Glen Torridon "have been more convincingly re-interpreted as a palimpsest landscape in which older moraines have been overprinted by flutes during the Younger Dryas" (p. 289). However, Wilson & Evans (2000) failed to address any of the detailed evidence presented by Bennett *et al.* (1998) in support of a thrust origin for the landforms, and presented little evidence in support of their own position. Their main line of evidence was the clarity of the "integrated network of ice-flow indicators" (p. 155) identified on aerial photographs, an interpretation with which we disagree.

Lukas (2005) placed great emphasis on our use of rectilinear faces as a diagnostic criterion for englacial thrust moraines. He is right to recognise that such faces may be produced by a variety of processes, and they are by no means limited to glacial landforms. We recognise that it is inappropriate to base the interpretation of a sediment-landform association on a single criterion -- especially one that may result from a variety of processes -- and our interpretations are based on a variety of criteria defined with reference to landforms in contemporary glacial environments, but not all of which may be identifiable at any particular location (Table 2). Lukas oversimplified the expected properties of englacial thrust moraines, stating that: "During glacier retreat, this material [englacially thrust sediment] is inferred to melt-out without alteration to leave a sequence of stacked moraines with characteristic rectilinear slopes" (p. 289). Whilst this is the essence of the model, the highly controlled morphology described represents one end of a continuum of landform types, the final morphology being controlled by the spacing and steepness of the thrusts (controlling the volume of buried ice) and the texture of the sediment (controlling the propensity to experience postglacial mobilization) (Bennett *et al.* 1998).

Lukas (2005) also misrepresented the sedimentological evidence in support of the englacial thrusting hypothesis, stating that, "sedimentological evidence in support of their model is restricted to shallow surface exposures" (p. 289). Actually, in Svalbard where the hypothesis was developed, vegetation is extremely sparse, there is complete sedimentary exposure, and sections are common (both in the glaciers themselves and in the landforms). Detailed evidence of the constituent facies and facies architecture of the moraines has been presented for numerous localities (e.g. Hambrey & Huddart 1995; Bennett *et al.* 1996b; 1999; Huddart & Hambrey 1996; Hambrey *et al.* 1999b). It is true that there is less evidence of the sediments associated with those British landforms that have been interpreted as thrust moraines. In the palaeo-landform context, where the sediments are commonly poorly exposed and the morphology has experienced thousands of years of post-glacial modification, it is rarely straightforward to determine unambiguously the genesis of individual sediment-landform associations. However, it appears that only total information would satisfy Lukas: "no detailed description or interpretation of the complete internal architecture of a moraine has ever been presented in support of this model" (2005: p. 289). In reality, it is only ever possible to sample the constituent sediments of a landform, and knowledge of the "complete internal architecture" is impossible, even where exposure is excellent as in Svalbard. Nevertheless, by comparing the available evidence against a variety of candidate models, it is often possible to determine the most probable genesis for a particular association. This is particularly true if a landsystems approach is adopted in which a spatial hierarchy of landscape elements is recognised: if the interpretations made at one scale are consistent with those at other scales this provides corroborative evidence that the individual elements have been correctly interpreted.

Conclusions

The evidence presented by Lukas (2005) on the internal structure of moraine-mound complexes in the northwest Scottish Highlands is a valuable contribution to the understanding of the dominant processes that produced these abundant sediment-landform associations. The paper supports the conclusions of earlier work that deglaciation on the Scottish mainland at the end of the Younger Dryas was characterised by active glacier recession and punctuated by numerous stillstands and minor readvances (Benn *et al.* 1992; Bennett & Boulton 1993a). Because the englacial thrusting model makes predictions about the internal structure of the resulting sediment-landform associations, detailed sedimentological analysis (such as that undertaken by Lukas) is a valid method of attempting to falsify the validity of the model at any particular site. However, a more general falsification of the model would require a demonstration that it is not valid at sites where englacial thrusting may plausibly have occurred, and where the morphological evidence is similar to that at the sites in Svalbard where thrusting is known to have occurred. We reject the assertion that the absence of evidence for englacial thrusting at the sites studied by Lukas implies that this process did not occur at other sites in Britain during the Younger Dryas. Englacial thrusting is not a universal explanation for the formation of moraine-mound complexes; it is simply another model to be considered when assessing their origin. Indeed, we have argued elsewhere (Bennett *et al.* 1998) that englacial thrusting is unlikely to have been widespread during the Younger Dryas, requiring the concurrence of a particular set of prevailing conditions. It has never been suggested that such conditions prevailed at the sites examined by Lukas.

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Table 1: Evidence for debris elevation by thrusting at contemporary glaciers

Direct observations	Displacements of up to 0.1 mh^{-1}. Total displacements of several metres (Sharp *et al.* 1988; Sharp *et al.* 1994).
Remote sensing observations	Sediment layers (of inferred thrust origin) detected by drilling (Clarke & Blake 1991) and ground-penetrating radar investigations (Murray *et al.* 1997).
Structural relationships in ice cliffs	Debris-bearing structures in ice cliffs showing evidence of displacement (Boulton 1970; Hart 1995; Bennett *et al.* 1996a)
Structural relationships on glacier surface	Interpretation of debris-bearing fractures as thrusts on basis of: (i) displacement of existing structures; (ii) mylonitised ice indicating recent activity; (iii) clean fracture with debris above; (iv) sharply defined zones of coarse clear ice formed by recrystallisation (Hambrey *et al.* 1996; 1999a; Glasser *et al.* 1998).
Isotopic data	Ice in debris-bearing fractures with isotopic composition indicative of open-system refreezing at the glacier bed (Hubbard *et al.* 2004).

Table 2: Evidence for a thrust origin for landforms (after Bennett *et al.* 1998). Not all characteristics may be present at a particular site

Morphological evidence	Sedimentological evidence
Broad moraine-mound belt	Facies variability between mounds
Common rectilinear upglacier faces with consistent dip and orientation	Each mound characterised by one facies/facies association
Steep and irregular downglacier faces	Abundant basally transported sediment
Imbricate/stacked morphology	Sharp, tectonic, facies contacts
Variable ridge/mound length	Fabrics: weak, girdle or random
Stacked on valley side	Primary depositional structures preserved